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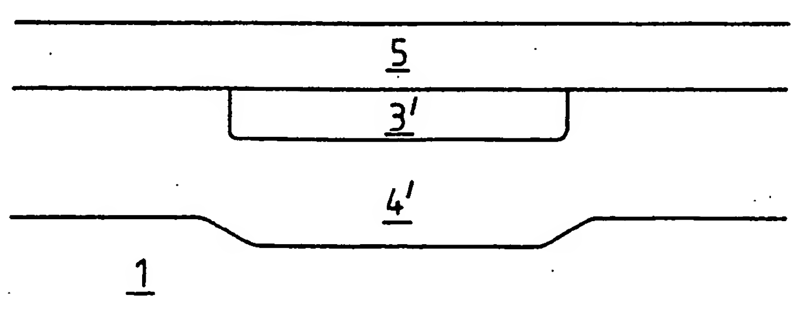

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(57) Abstract

A method of fabricating an optical waveguide includes the initial step of forming a strip (3) of doped silicon in a silicon substrate (1). The substrate (1) is then subjected to a porous anodisation step, whereby the doped silicon strip (3) is converted to a porous structure. The substrate (1) is then nitrided, whereby the porous structure (3) is converted to a substantially fully-dense silicon oxynitride matrix (3'). A doped silicon region (4) is then formed around the silicon oxynitride matrix (3'). The substrate (1) is then subjected to a second anodisation step, whereby the doped region (4) is converted into a porous structure (4'). The substrate (1) is then oxidised whereby the porous structure (4') is converted to a substantially fully-dense silicon dioxide matrix. Finally, an oxide layer (5) may be formed on top of the substrate (1).

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WAVEGUIDE FABRICATION

This invention relates to a method of fabricating an optical waveguide, and in particular to a waveguide fabrication method involving double porous anodisation of silicon.

It is known to fabricate strip waveguides on silicon substrates, using deposition and etching techniques, by forming a strip of relatively high refractive index material surrounded by relatively low refractive index material. The high refractive index material forms the core of the waveguide. The main disadvantage of this known fabrication process is that the waveguide core is formed by etching, and this results in the side walls of the core being rough, thereby leading to scattering losses in the finished waveguide. This process also requires the deposition of thick films which are difficult to process and can lead to stress problems. Another problem with a waveguide made in this manner is that it has a non-planar upper surface, which makes subsequent processing very difficult.

In some cases, it is advantageous to dope the core of the waveguide (for example with erbium or neodymium) to enable the waveguide to be used as an active optical component such as an amplifier or a laser. Using standard fabrication processes, this doping is difficult to achieve.

The aim of the invention is to provide an improved method of fabricating an optical waveguide and particularly a doped waveguide.

The present invention provides a method of fabricating an optical waveguide, the method comprising the steps of:-

(i) forming a strip of doped silicon in a silicon substrate;

(ii) subjecting the substrate to a first porous anodisation step, whereby the doped silicon strip is converted to a porous structure;

(iii) subjecting the substrate to a nitridation step, whereby the porous structure is converted to a substantially fully-dense matrix of silicon nitride or silicon oxynitride;

(iv) forming a doped silicon region surrounding said matrix;

(v) subjecting the substrate to a second porous anodisation step, whereby the doped region surrounding said matrix is converted into a porous structure; and

(vi) subjecting the substrate to an oxidation process, whereby the porous structure surrounding said matrix is converted to a substantially fully-dense silicon dioxide layer.

In a preferred embodiment, an oxide cladding layer is formed on top of the substrate, said oxide layer overlying said matrix. This results in a buried waveguide whose core is completely surrounded by oxide, thereby resulting in a more uniform optical mode. As an alternative to the oxide cladding layer, other overlay materials could be used to change the properties of the waveguide, for example by plasma interaction with a metal.

Advantageously, each of the porous anodisation steps is carried out by placing the substrate in an electrochemical cell in an HF solution.

In a preferred embodiment, the strip of doped silicon is formed in the substrate by a boron diffusion step. Conveniently, the boron diffusion is carried out through a

mask formed photolithographically on the surface of the substrate.

Preferably, the nitridation step is carried out by heating the substrate in an atmosphere of ammonia, the nitridation process comprising the steps of:-

(i) loading the substrate into a furnace at 200°C;

(ii) subjecting the substrate to a ramped annealing step until the temperature reaches 725°C, the rate of temperature increase during the ramped annealing step being 8°C per minute; and

(iii) heating the substrate at 725°C for 60 minutes;

each of said steps being carried out in an atmosphere of ammonia at 0.5 bar.

Advantageously, the doped region surrounding said matrix is formed by a boron diffusion process.

Preferably, the oxidation process is carried out by heating the substrate in dry oxygen, the oxidation process comprising the steps of:-

(i) heating the substrate for 60 minutes at a temperature of 350°C in dry oxygen;

(ii) subjecting the substrate to a ramped annealing step in steam, the rate of temperature increase during the ramped annealing step being 4°C per minute until the temperature reaches 1,150°C; and

(iii) heating the substrate for 10 minutes at 1,150°C in steam.

Conveniently, the oxide cladding layer is formed by a deposition technique such as chemical vapour deposition (CVD) or plasma enhanced chemical vapour deposition (PECVD).

The invention will now be described in greater detail, by way of example, with reference to the accompanying drawings, in which:-

Figs. 1 to 4 are schematic longitudinal cross-sections which illustrate the basic process sequence of the fabrication method of the invention.

Referring to the drawings, Fig. 1 shows an n-type silicon substrate 1. An oxide layer is then formed on the substrate 1, the oxide layer being 1μm thick and being subjected to a photolithographic process to form a mask 2. Boron is then diffused into the substrate 1 through the mask 2. The boron diffusion process defines a strip 3 of p^+ silicon which is capable of supporting a fine porous structure in a subsequent anodisation step. The diffusion schedule can be carefully controlled to provide a precise depth (typically between 0.25 and 5μm) for the strip 3 which is to constitute the core of the waveguide. This stage of the process is shown in Fig. 1. The mask 2 is then stripped off using a buffered HF etchant.

The substrate 1 is then subjected to porous anodisation, that is to say it is placed in an electrochemical cell in an HF solution. The HF attacks the p^+ silicon to form a porous structure having a very large surface area. The HF attacks the doped p^+ silicon preferentially, so that the porous anodisation is substantially restricted to the strip 3. The size and density of the pores in the strip 3 depend upon the current density flowing in the cell. The current density is of the order of 10mA/cm^2, so that a subsequent nitridation step results in a substantially fully-dense, stress-free matrix.

Following anodisation, the substrate 1 is subjected to a nitridation step, during which the porous structure of the strip 3 has its volume porousity substantially filled with silicon oxynitride. This is accomplished by loading

the substrate 1 into a furnace at a temperature of 200°C, subjecting the substrate to a ramped annealing step (the rate of temperature increase during this ramped annealing step being 8°C per minute) until the temperature reaches 725°C, and holding the substrate at this temperature for 60 minutes. The entire heating process is carried out under 0.5bar of ammonia. This results in a substantially fully-dense (> 90%) silicon oxynitride matrix 3' which is substantially stress-free.

Boron is then diffused into the substrate 1 to form a p^+ doped silicon layer 4. Once again, the depth of the p^+ layer 4 can be accurately controlled, preferably to a depth of between 4 and 5μm below the base of the silicon oxynitride matrix 3' (i.e. an overall depth of about 5 to 10 μm). The substrate 1 is then subjected to a second porous anodisation step, in which the HF in the electrochemical cell preferentially attacks the p^+ layer 4 to form a porous structure. In practice, the region of the p^+ layer below the matrix 3' is found to be deeper than the rest of the layer 4. This is believed to be caused by enhanced diffusion of boron through residual pores, or by stress in the matrix 3'. Alternatively, boron in the matrix 3' could be snow-ploughed into the substrate 1 during the nitridation step. This stage of the process is shown in Fig. 2.

The porous p^+ structure 4 is then converted to a silicon dioxide matrix 4', which encapsulates the silicon oxynitride matrix 3', by an oxidation process. This process starts with a 60 minute low temperature (350°C) anneal in dry oxygen, and finishes with a 10 minute anneal at 1150°C in steam, a ramped anneal in steam taking place between the two other heating steps. The rate of temperature increase during the ramped anneal step is 4°C per minute. This stage of the process is shown in Fig. 3.

Finally, an oxide cladding layer 5 2μm thick is deposited on the top of the substrate 1 (and overlying the silicon oxynitride matrix 3') by low pressure chemical vapour deposition (LPCVD) or by plasma-enhanced chemical vapour deposition (PECVD). This stage of the process is shown in Fig. 4. This cladding layer 5 completes the encapsulation of the oxynitride strip 3 by oxide layers. As silicon oxynitride has a slighter higher refactive index than silicon dioxide, the strip 3 forms the waveguiding core of a strip waveguide.

The oxide cladding layer 5 is optional, as a useful waveguide is produced at the Fig. 3 stage. The layer 5 is preferable, however, as it results in a buried waveguide whose core (the matrix 3') is completely surrounded by oxide. This results in a waveguide which has a more uniform optical mode. As an alternative to the oxide cladding layer 5, other cladding materials may be used to change the properties of the waveguide, for example by plasma interaction with a metal.

If the waveguide is to be used as an active optical component (such as an amplifier or a laser) its core (the matrix 3') is doped with an optically-active material such as erbium or neodymium. This doping step is carried out after the first porous anodisation step and before the nitridation step.

A waveguide fabricated in this manner has the following useful properties, namely:-

(i) the sidewalls of the waveguiding core (the matrix 3') are smooth, having been defined by the first boron diffusion profile;

(ii) the depth of the waveguiding core can be accurately controlled by careful control of the first boron diffusion;

(iii) being porous, the waveguiding core is easy to dope (for example with erbium), so the waveguide can be used an an active optical component such as an amplifier or a laser;

(iv) the only photolithographic step occurs at the very first stage of processing; and

(v) it has a planar upper surface, so that subsequent processing is facilitated. The waveguide has a planar upper surface, both before and after the formation of the oxide cladding layer, so that subsequent processing is facilitated whether or not this optional cladding layer is present. If the cladding layer 5 is present, subsequent processing can include the opening up of windows in the cladding layer to provide selective regions of active overlay (for example for making sensors).

CLAIMS

1. A method of fabricating an optical waveguide, the method comprising the steps of:-

(i) forming a strip of doped silicon in a silicon substrate;

(ii) subjecting the substrate to a first porous anodisation step, whereby the doped silicon strip is converted to a porous structure;

(iii) subjecting the substrate to a nitridation step, whereby the porous structure is converted to a substantially fully-dense matrix of silicon nitride or silicon oxynitride;

(iv) forming a doped silicon region surrounding said matrix;

(v) subjecting the substrate to a second porous anodisation step, whereby the doped region surrounding said matrix is converted into a porous structure; and

(vi) subjecting the substrate to an oxidation process, whereby the porous structure surrounding said matrix is converted to a substantially fully-dense silicon dioxide layer.

2. A method as claimed in claim 1, further comprising the step of forming an oxide cladding layer on top of the substrate, said oxide layer overlying said matrix.

3. A method as claimed in claim 1 or claim 2, wherein each of the porous anodisation steps is carried out by placing the substrate in an electrochemical cell in an HF solution.

4. A method as claimed in any one of claims 1 to 3, wherein the strip of doped silicon is formed in the substrate by a boron diffusion step.

5. A method as claimed in claim 4, wherein the boron diffusion is carried out through a mask formed photolithographically on the surface of the substrate.

6. A method as claimed in any one of claims 1 to 5, wherein the nitridation step is carried out by heating the substrate in an atmosphere of ammonia.

7. A method as claimed in claim 6, wherein the nitridation process comprises the steps of:-

(i) loading the substrate into a furnace at 200°C;

(ii) subjecting the substrate to a ramped annealing step until the temperature reaches 725°C, the rate of temperature increase during the ramped annealing step being 8°C per minute; and

(iii) heating the substrate at 725°C for 60 minutes;

each of said steps being carried out in an atmosphere of ammonia at 0.5 bar.

8. A method as claimed in any one of claims 1 to 7, wherein the doped region surrounding said matrix is formed by a boron diffusion process.

9. A method as claimed in any one of claims 1 to 8, wherein the oxidation process is carried out by heating the substrate in dry oxygen.

10. A method as claimed in claim 9, wherein the oxidation process comprises the steps of:-

(i) heating the substrate for 60 minutes at a temperature of 350°C in dry oxygen;

(ii) subjecting the substrate to a ramped annealing step in steam, the rate of temperature increase during the ramped annealing step being 4°C per minute until the temperature reaches 1,150°C; and
(iii) heating the substrate for 10 minutes at 1,150°C in steam.

11. A method as claimed in any one of claims 1 to 10, wherein the oxide layer is formed by chemical vapour deposition.

12. A method as claimed in any one of claims 1 to 11, further comprising the step of doping the porous structure formed during the first porous anodisation step with erbium or neodymium, this doping step being carried out prior to the nitridation step.

13. A method of forming an optical waveguide substantially as hereinbefore described with reference to, and as illustrated by, the accompanying drawings.

14. An optical waveguide whenever fabricated by the method of any one of claims 1 to 13.

15. An active optical component comprising at least one waveguide as claimed in claim 14.

Fig.1.

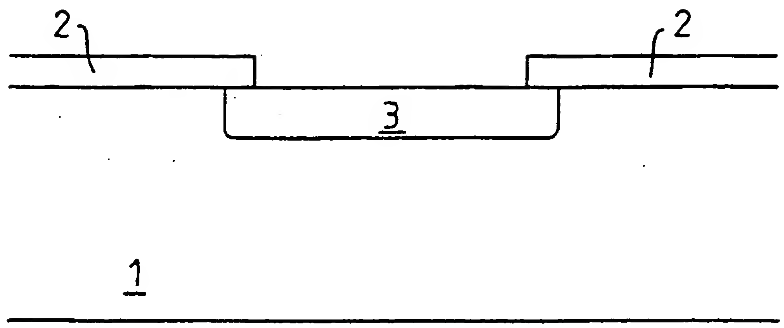


Fig.2.

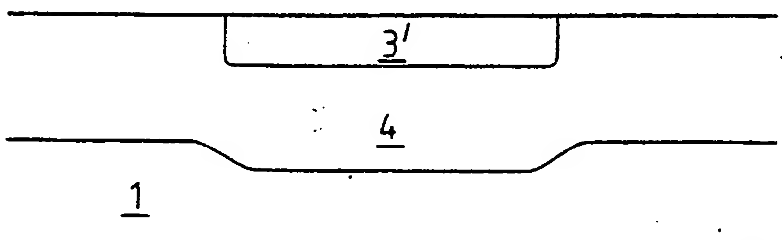


Fig.3.

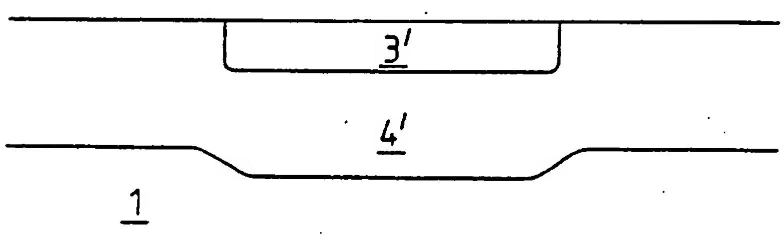
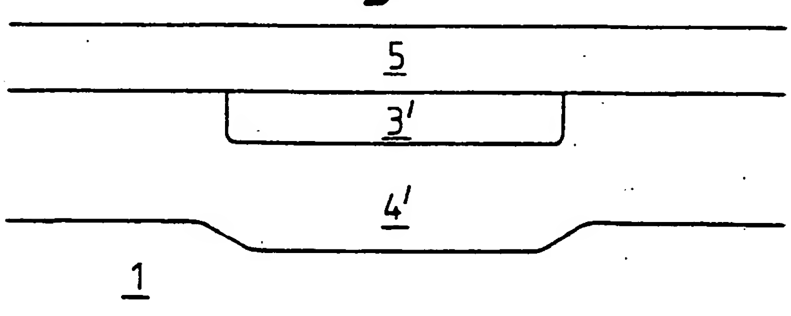


Fig.4.



INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 91/00044

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^5: G 02 B 6/12

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^5	G 02 B 6/00, H 01 S 3/00

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
A	Applied Physics Letters, vol. 47, no. 4, August 1985 American Institut of Physics, New York (US) D.E. Zelmon et al.: "Low loss optical waveguides fabricated by thermal nitridation of oxidized silicon", pages 353-355, see the whole article --	1,6,7,13,14
A	Applied Optics, vol. 16, no. 12, December 1977, W. Stutius et al.: "Silicon nitride films on silicon for optical waveguides", pages 3218-3222 see the whole article --	1,13,14
A	Patent Abstracts of Japan, vol. 13, no. 547, (P-971)(3895), 7 December 1989, & JP, A, 1227104 (FUJIKURA LTD) 11 September 1989	1,13,14

* Special categories of cited documents: [10]

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
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